

Recent results of the ANTARES Neutrino Telescope

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Abstract

The latest results from the ANTARES Neutrino Telescope are reported. Limits on a high energy neutrino diffuse flux have been set using for the first time both muon-track and showering events. The results for point sources obtained by ANTARES are also shown. These are the most stringent limits for the southern sky for neutrino energies below 100 TeV. Constraints on the nature of the cluster of neutrino events near the Galactic Centre observed by IceCube are also reported. In particular, ANTARES data excludes a single point-like neutrino source as the origin of this cluster. Looking for neutrinos coming from the Sun or the centre of the Galaxy, very competitive limits are set by the ANTARES data to the flux of neutrinos produced by self-annihilation of weakly interacting massive particles.

1. Introduction

Several astrophysical objects both Galactic and extra-galactic have been proposed as sites of acceleration of protons and nuclei, but no conclusive experimental evidence has been obtained yet and in any case in-depth experimental studies of the cosmic hadronic accelerators are lacking. The decays of mesons produced by the interactions of protons and nuclei with matter or radiation would yield neutrinos, thus indicating the presence of this type of acceleration. The detection of high energy cosmic neutrinos can therefore shed light on the origin of cosmic rays. Furthermore, neutrinos are at the end of a variety of decay chains of standard (and beyond the standard) model particles, being therefore an exceedingly useful “debris” to look for different processes, such as for instance the self-annihilation of the hypothetical weakly interacting massive particles that could form the dark matter in the Universe.

Let us briefly summarize the advantages of neutrinos as cosmic messengers. They are neutral particles, therefore they are not deflected by magnetic fields and point back to their sources. They are weakly interacting and thus can escape from very dense astrophysical objects and travel long distances without being absorbed by matter or background radiation. Moreover, in cosmic sites where

hadrons are accelerated, neutrinos are generated in the decay of charged pions produced in the interaction of those hadrons with the surrounding matter or radiation, being therefore a smoking gun of hadronic acceleration mechanisms.

Several neutrino telescopes are at present operating worldwide and larger telescopes or extensions of the already existing are planned. The breakthrough in this field took place in 2013 with the announcement by the IceCube collaboration of the first evidence of a cosmic signal of high energy neutrinos [1] with the subsequent confirmation of the signal with more data [2].

Here we report the recent results of the ANTARES neutrino telescope. Even though of a much smaller size than IceCube, ANTARES is capable of providing useful information both in the search of neutrino astrophysical sources and that of indirect dark matter, as we show in this contribution.

2. The ANTARES telescope

The ANTARES Collaboration completed the construction of its namesake neutrino telescope in the Mediterranean Sea in May 2008, although a partial version of the device was operating since 2007. The telescope, located 40 km off the southern coast of France ($42^{\circ}48'N$, $6^{\circ}10'E$) at a depth between 2475 m (seabed) and 2025 m (top of the lines), consists in a three-dimensional array of photomultipliers housed in glass spheres, called optical modules, distributed along twelve lines anchored to the sea bottom and kept taut by a buoy at the top. Each line is composed of 25 storeys of triplets of optical modules (OMs), each housing one 10-inch photomultiplier. The lines are subjected to the sea currents and can change shape and orientation. A positioning system based on hydrophones, compasses and tiltmeters is used to monitor the detector geometry with an accuracy of about 10 cm. More details of the ANTARES telescope can be found in ref. [3].

The goal of the experiment is to search for neutrinos with energies greater than ~ 50 GeV mainly by detecting muons. A muon neutrino that has crossed the Earth can undergo a charged current interaction before arriving to the detector and produce a muon that can travel hundreds of metres and cross the telescope. Muons induce the emission of Cherenkov light in sea water and the arrival time and intensity of this light on the OMs are digitized into hits and transmitted to shore. Events containing muons are selected from the continuous deep-sea optical backgrounds due to natural radioactivity and bioluminescence. The arrival time of the Cherenkov photons can be determined at the nanosecond level [4], allowing the measurement of the direction of upgoing tracks with resolutions better than 0.5° for neutrino energies above 1 TeV. Due to the large background from downgoing atmospheric muons, the telescope is optimised for the detection of upgoing muons that can only originate from neutrinos. Recently, also neutrino-induced shower events are being reconstructed increasing the reach of the detector in terms of detectable neutrino types.

3. Diffuse fluxes

A search for a neutrino diffuse flux using upgoing muon neutrino events has been performed using the data recorded from 2007 to 2011, corresponding to a total livetime of 885 days (throughout this contribution, the words *neutrino* and *muon* are meant to include also their antiparticle). The analysis first imposes loose cuts on the muon track reconstruction quality parameter and the angular error estimate obtained by the reconstruction fit to reduce the background. On this reduced sample, optimised cuts are then applied to the quality parameter and the number of hits in the event, used as a proxy of the neutrino energy, whose spectrum is expected to be harder for the signal than for the background. The optimisation of the cuts was carried out following a blinding procedure, i.e. on simulated data and accessing only 10% of the total data sample which was subsequently discarded for the final analysis. After unblinding, i.e. when applying the selection to the data, 8 events pass the cuts while the expected background is 8.4 events.

This corresponds to a 90% confidence level upper limit (à la Feldman-Cousins with systematic errors included):

$$E^{-2} \cdot \Phi_{90\%} = 5.1 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (1)$$

in the energy range from 45 TeV to 10 PeV. This limit is shown in Fig. 1

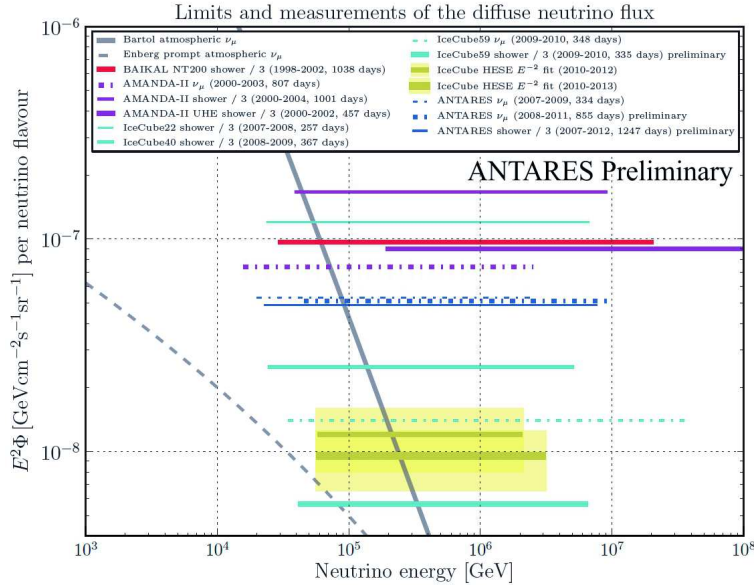


Figure 1: 90% C.L. upper limits to an E^{-2} diffuse neutrino flux for different experiments and analyses. The ANTARES upper limits (blue lines) set by the muon neutrino and showering event analyses are 5.1 and $4.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, respectively. See text for explanations.

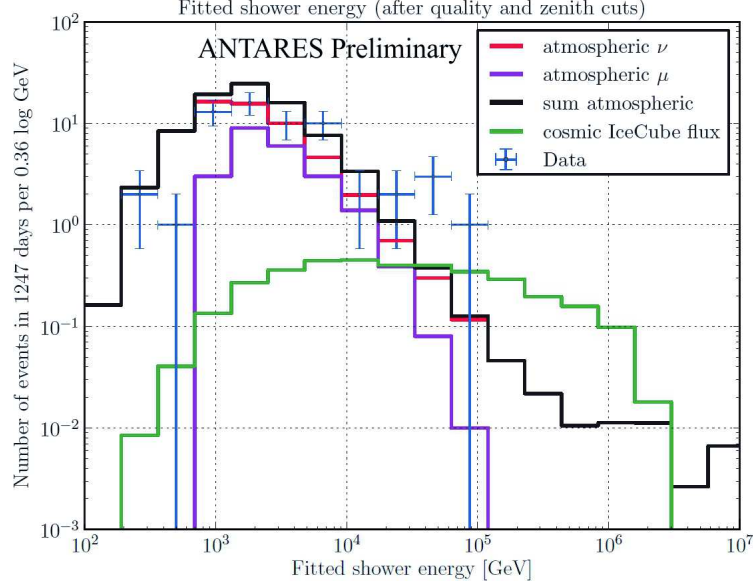


Figure 2: Distribution of the reconstructed energy of the selected shower events before the final energy cut. The data are the points with errors. The expected background contributions are also shown: atmospheric neutrinos (red line), atmospheric muons (purple line), sum of both (black line). Finally, how a flux of the magnitude of that observed by IceCube’s high-energy starting events would look like is also represented. See text for explanations.

An alternative analysis was performed that included various event parameters and an optimal set of event selection criteria were found by scanning this parameter space. One of the parameters was the energy of the event, which was estimated in this case by an artificial neural network. The livetime in this analysis was slightly higher, 900 days, but the final sensitivity was very similar to the previous analysis: $4.2 \times \Phi_0$ versus $4.7 \times \Phi_0$ for the previous analysis (where $\Phi_0 = 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$). After unblinding, 12 events pass the cuts on an expected background of 8.4 events. This small excess interpreted as a background fluctuation gives a 90% C.L. limit slightly higher but fully compatible with the previous result, $7.7 \times \Phi_0$ versus $5.1 \times \Phi_0$, in a similar energy range (from 65 TeV to 10 PeV),

The search for a diffuse neutrino flux has also been performed using shower events. The shower reconstruction algorithm first selects good signal hits from all the recorded PMT signals in the event. From these selected hits, the interaction vertex location and time are reconstructed using a maximum likelihood method. From this vertex and using the shower signal hits the energy and the neutrino direction are estimated.

After the muon suppression cut (see later), the median vertex and direction errors are 4 metres and 6° , respectively, for 10 TeV showers, and the logarithm of the energy ($\log(E_{fit}/E_{MC})$) is reconstructed with an error of -0.16 for showers of 10 TeV. Of all the simulated showers, 40% are reconstructed and pass the

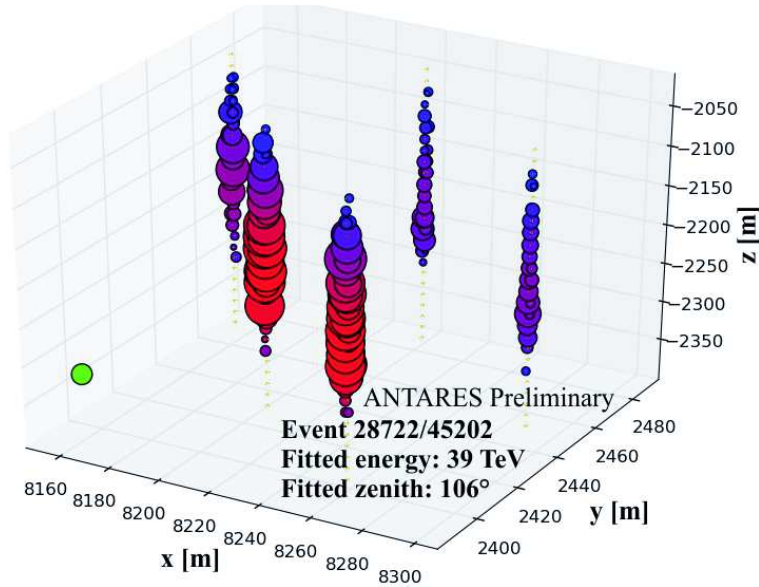


Figure 3: Example of shower event that passes the selection criteria.

muon cut at 10 TeV and 90% at 10 PeV. At this level, the muon rejection power is of the order of 10^5 .

Once the shower is reconstructed a series of selection criteria are imposed. First, a muon filter is used to reject those events that may be compatible with a muon track. The events are then required to be reconstructed in more than two lines. Although unfrequent, some optical modules produce from time to time sparks that could imitate a shower. A special filter based on a minimum distance of the reconstructed shower vertex to any OM is used to reject these events. Finally, the event is required to be upgoing (fitted zenith angle greater than 94°) and the reconstructed energy of the shower should be higher than 10 TeV.

The expected background after this selection criteria is 4.9 events, coming mainly from atmospheric neutrinos (3.1 events) and muons (1.9 events). The systematic error on the total background is ± 2.9 events. In Fig. 2 the distribution in energy of all the events before the final cut on reconstructed energy is shown.

After unblinding, 8 shower events pass all the cuts. In Fig. 3, one of the events is shown. The probability to obtain 8 or more background events when 4.9 are expected is 12.5% (1.5σ). Therefore, this excess is interpreted as a background fluctuation and the following 90% confidence level upper limit on a cosmic signal is extracted using Feldman–Cousins and taking into account the systematic uncertainties:

$$E^{-2} \cdot \Phi_{90\%} = 4.91 \times 10^{-8} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad (2)$$

in the energy range from 23 TeV to 7.8 PeV. This limit is shown in Fig. 1.

Given the cosmic signal observed in IceCube [2], namely: $1.0 \pm 0.3 \times \Phi_0$ (where again, $\Phi_0 = 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) with a hard cut-off at 1.6 PeV, one may wonder to which flux the ANTARES excess of shower events would correspond if interpreted as a cosmic signal. The answer is that with an unbroken E^{-2} spectrum the excess corresponds to a flux intensity of $1.3_{-1.3}^{+1.8} \times \Phi_0$, and to $1.7_{-1.8}^{+2.3} \times \Phi_0$, assuming a cut-off at 2 PeV. Therefore, we cannot also exclude either that this excess is not a background fluctuation, but lack of statistics prevent us from making any claim.

4. Search for point sources

Although already published [5], we want to report briefly on some of the results of the search for neutrino point sources recently released by ANTARES, because of their impact on the recent signal observed by the IceCube collaboration [1, 2]. The data used for this analysis were recorded between 2007 and 2012 and correspond to a total livetime of 1338 days. Upgoing muon neutrino events leaving a well-reconstructed muon track in the detector were searched for. The parameters used to select the events were the reconstruction quality of the corresponding track, its angular uncertainty as estimated by the fit and its zenith angle. The exact values of these parameters were chosen so that the neutrino flux required to make a 5σ discovery with 50% probability was minimised. As usual, this minimisation was performed following a blind procedure, i.e. using pseudo-experiments before performing the analysis on the data. After unblinding, the selection gave a total of 5516 events, which included an estimated background of 10% of misreconstructed atmospheric muons. Signal events are expected to accumulate in clusters over the diffuse background of atmospheric neutrinos. The search for clusters is performed with a maximum likelihood method fed with information about the angular error estimate of the events and their energy via the number of observed hits in the event. The minimisation provides a number of signal events and a test statistic from which we can extract the probability of the observation to be produced by the expected background (p -value).

The full-sky search looks for an excess anywhere in the part of the sky visible to ANTARES. After unblinding, the most significant cluster found had a 2.7% post-trial p -value (a 2.2σ effect). This is not significant enough to claim a signal. The 90% confidence level limits on the muon neutrino flux from point sources extracted from the absence of a signal are given in declination bands of 1° by the light blue-dashed line in Fig. 4. A second search is done using a list of 50 candidate sources (see ref. [5]). In this case, the largest post-trial p -value is 6.1% (1.9σ) for the candidate source HESS J0632+057. The limits for these 50 sources are given in Fig. 4 by the large blue squares and the sensitivity is given by the thin blue line. The corresponding limits and sensitivity are given by the red squares and thin line, respectively. One is tempted to conclude that even for part of the southern sky (negative declinations) IceCube has a better

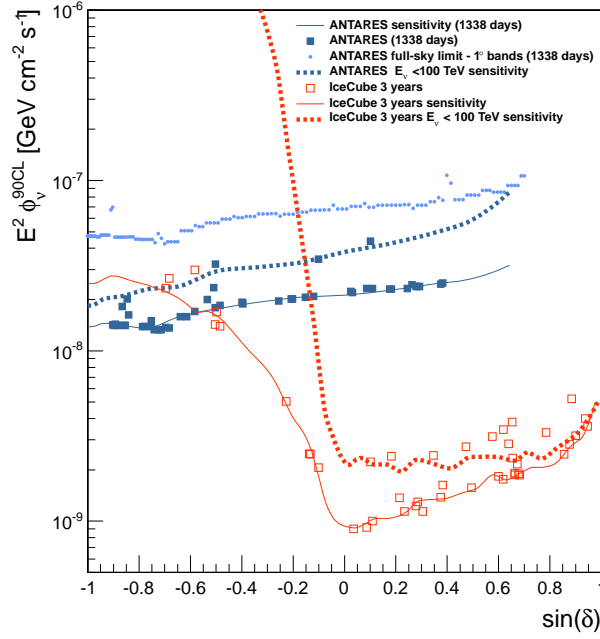


Figure 4: 90% C.L. flux upper limits and sensitivities on the muon neutrino flux for six years of ANTARES data. IceCube results are also shown for comparison. The light-blue markers show the upper limit for any point source located in the ANTARES visible sky in declination bands of 1° . The solid blue (red) line indicates the ANTARES (IceCube) sensitivity for a point-source with an E^{-2} spectrum as a function of the declination. The blue (red) squares represent the upper limits for the ANTARES (IceCube) candidate sources. Finally, the dashed dark blue (red) line indicates the ANTARES (IceCube) sensitivity for a point-source and for neutrino energies lower than 100 TeV, which shows that the IceCube sensitivity for sources in the southern hemisphere is mostly due to events of higher energy. The IceCube results were derived from ref. [6].

sensitivity, but given their selection method for those declinations (basically very high energy downgoing events), this limit only applies for the high energy region, where Galactic sources are not expected to have a sizeable fraction of their emission. This is better seen comparing the blue (ANTARES) and red (IceCube) small-square lines for which the sensitivity is given with the constraint $E_\nu < 100$ TeV. While the ANTARES sensitivity marginally decreases, that of IceCube practically disappears for southern sky sources.

A point source close to the Galactic Centre has been proposed [7] as a possible explanation to the accumulation of seven events in its neighbourhood in the first sample of cosmic neutrinos announced by IceCube [1]. The corresponding normalization of the flux of this source would be $6 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}$ and would be located around $\alpha = -79^\circ$, $\delta = -23^\circ$. However, due to the large error

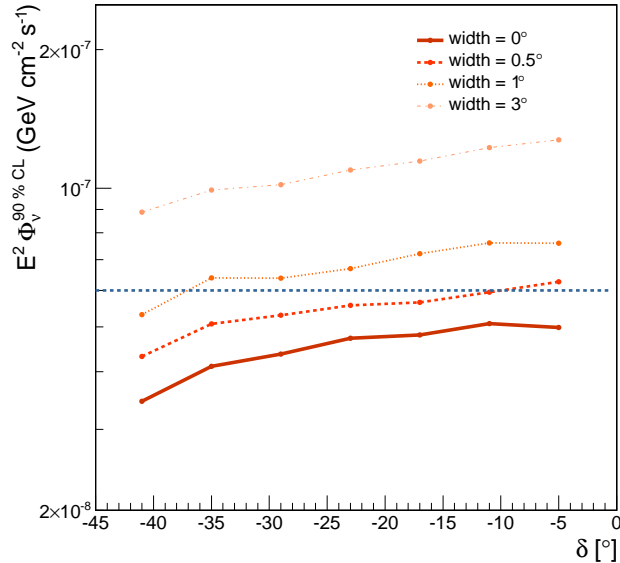


Figure 5: 90% C.L. upper limits obtained for different source widths as a function of the declination. The blue horizontal dashed line corresponds to the signal flux given in ref. [7].

on the direction estimates of these IceCube events, if present, the location of the source would have a high uncertainty. We have performed a search in a region of 20° around the proposed location. The trial factor of this analysis is smaller than that of the full-sky search because of the smaller size of the region. In addition to the point source hypothesis, three Gaussian-like source extensions are assumed (0.5° , 1° and 3°). No significant cluster has been found. Fig. 5 shows the 90% CL flux upper limits obtained for the spatial extensions of the neutrino source as a function of the declination. The presence of a point source with a flux normalization of $6 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}$ anywhere in the region is excluded. Therefore, the excess found by IceCube in this region cannot be caused by a single point source. Furthermore, a source width of 0.5° for declinations lower than -11° is also excluded. The results are not affected by a cutoff at energies of the order of PeV, since for an E^{-2} spectrum the contribution of neutrinos above that energy is small, of the order of a few percent.

5. Indirect search for dark matter

If dark matter is composed of weakly interacting massive particles (WIMPs), these would tend to accumulate by elastic scattering and the gravitational pull in the centre of massive astrophysical objects like stars, galaxies and clusters of galaxies. There they can annihilate and produce standard model particles

whose decays would produce neutrinos that can be detected at Earth. In some cases, e.g. the Sun, the high energy neutrino background expected from normal astrophysical processes is very small, so a bunch of high energy neutrinos would be enough to claim a signal. ANTARES has looked for high energy neutrinos coming from the Sun and the centre of our Galaxy.

The ANTARES search for high energy neutrinos coming from the annihilation of WIMPs in the centre of the Sun used data collected during 2007 and 2008 corresponding to a livetime of 295 days. The search was performed using up-going neutrino events whose direction pointed back to the Sun. Simulated data was used to optimise the cuts on the reconstruction quality of the muon track produced by the neutrino and on the angular separation of the neutrino and the Sun direction. The simulated data included WIMP annihilation to $b\bar{b}$, W^+W^- and $\tau^+\tau^-$ without any model assumption, i.e. with the same 100% branching ratios for all the channels. The cuts on the track reconstruction quality and on the opening angle of the cone around the Sun for which tracks were accepted were obtained optimising the model rejection factor for each WIMP mass and each channel. After unblinding, the number of selected events was in agreement, within the statistical errors, with background expectations. Upper limits at the 90% confidence level on the flux of a neutrino signal as a function of the WIMP mass were obtained using Poisson statistics with the Feldman-Cousins recipe for all the three channels [8]. Assuming equilibrium between the WIMP capture and self-annihilation rates in the Sun, limits on the spin-independent (SI) and spin-dependent (SD) WIMP-proton scattering cross-sections can be obtained.

Fig. 6 shows the limits for the spin-dependent WIMP-proton cross-section, case in which the limits imposed by neutrino telescopes are in general very competitive, because the capture rate is very sensitive to this cross-section since the Sun is mostly composed of protons. The colour of the curves in the figure indicate the channel, green for $b\bar{b}$, blue for W^+W^- and red for $\tau^+\tau^-$. The type of line indicates the experiment which set the corresponding limits: solid lines for ANTARES (2007-2008), dashed-dotted for Baksan (1978-2009) [9], dotted for Super-Kamiokande (1996-2008) [10] and dashed lines for IceCube-79 (2010-2011) [11]. The black lines correspond to the limits imposed by direct search experiments: short dot-dashed lines for SIMPLE (2004-2011) [12] and long dot-dashed for COUPP (2010-2011) [13]. Also shown are the results of a grid scan of the CMSSM and MSSM-7, the dark and light grey shaded areas, respectively. As can be seen, ANTARES limits are very competitive with respect to other experiments and skim the region predicted by MSSM-7.

As in the case of the Sun, WIMPs can also accumulate in the centre of the Galaxy and annihilate producing neutrinos. We have used the data recorded by ANTARES between 2007 and 2012, corresponding to a livetime of 1321 days, to search for neutrinos coming from the Galactic Centre. The method is similar to that of the Sun, but in this case two reconstruction strategies that complement each other in different WIMP mass ranges have been used. Events reconstructed in one single line have also been used: these lack the measurement of the azimuth angle and therefore the expected background increases slightly, but this is compensated by the increase in statistics. As in the previous analysis

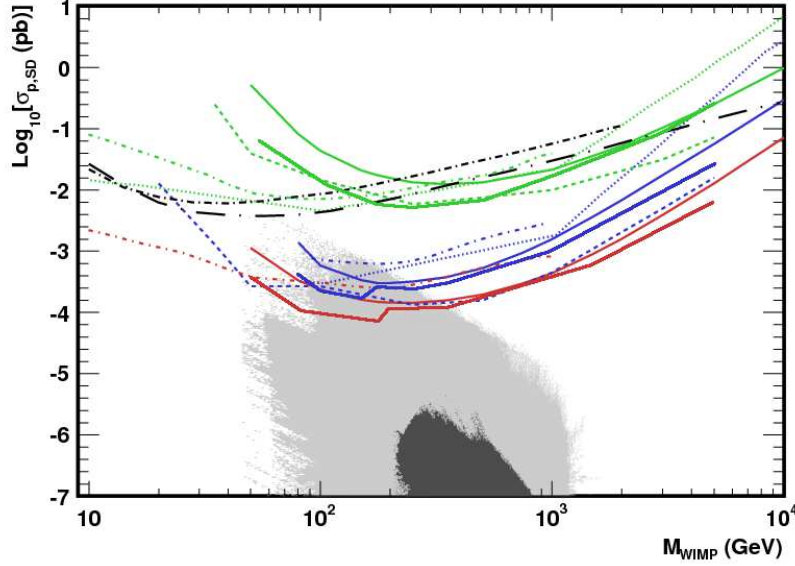


Figure 6: 90% C.L. upper limits on the spin-dependent WIMP-proton cross-section as a function of the WIMP mass derived from the neutrino flux limits from the Sun for the three self-annihilation channels $b\bar{b}$ (green lines), W^+W^- (blue lines) and $\tau^+\tau^-$ (red lines). The type of line indicates the experiment which set the corresponding limits: solid lines for ANTARES, dashed-dotted for Baksan (1978-2009), dotted for Super-Kamiokande (1996-2008) and dashed lines for IceCube-79 (2010-2011). The black lines correspond to the limits imposed by direct search experiments: short dot-dashed lines for SIMPLE (2004-2011) and long dot-dashed for COUPP (2010-2011). The dark and light grey shaded areas show the results of a grid scan of the CMSSM and MSSM-7 SUSY models, respectively. See text for references.

the cuts on the quality parameter –given in this case by one or the other of the reconstruction strategies– and on the angular separation of the track with respect to the position of the Galactic Centre are optimised using a model rejection factor. After unblinding, the number of events found are in agreement with those expected for the background and thus limits are imposed on the neutrino fluxes for each of the different annihilation channels. A useful quantity to compare among experiments that use different techniques to detect dark matter is the velocity averaged WIMP self-annihilation cross-section, $\langle \sigma_A \cdot v \rangle$. To extract this quantity from the limits on the neutrino flux, some assumptions have to be made. First, a distribution has to be assumed for the density profile of the dark matter in the Galaxy, ρ_{DM} , that enters into the flux estimation through the so-called J-factor, i.e. the integral along the line of sight of the square of the WIMP density:

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int \rho_{DM}^2 dl d\Omega \quad (3)$$

We use the Navarro-Frenk-White galactic dark matter halo profile [14], with

a parameter $r_s=21.7$ kpc and normalised in such a way that at the Sun's position the density is 0.4 GeV cm^{-3} . In Fig.7, the red line indicates our 90% confidence level upper limit on $\langle \sigma_A \cdot v \rangle$ obtained for the reference $\tau^+\tau^-$ channel. For the sake of comparison, the following limits on $\langle \sigma_A \cdot v \rangle$ are also given: IceCube–DeepCore 79 (2010-2011) for the Galactic Centre indicated by the blue line [15], IceCube–59 (2009-2010) for the Virgo cluster given by the black line [16], Fermi-LAT (2008-2010) for the joint analysis of 10 satellite galaxies given by the green line [17] and MAGIC (2011-2013) for Segue 1 given by the purple line [18]. The regions favored by PAMELA (orange area) and by PAMELA, Fermi-LAT and H.E.S.S. (green ellipses) interpreted as dark matter self-annihilations are also shown [19]. The gray band indicates the natural scale for which all the dark matter is considered to be composed of WIMPs only.

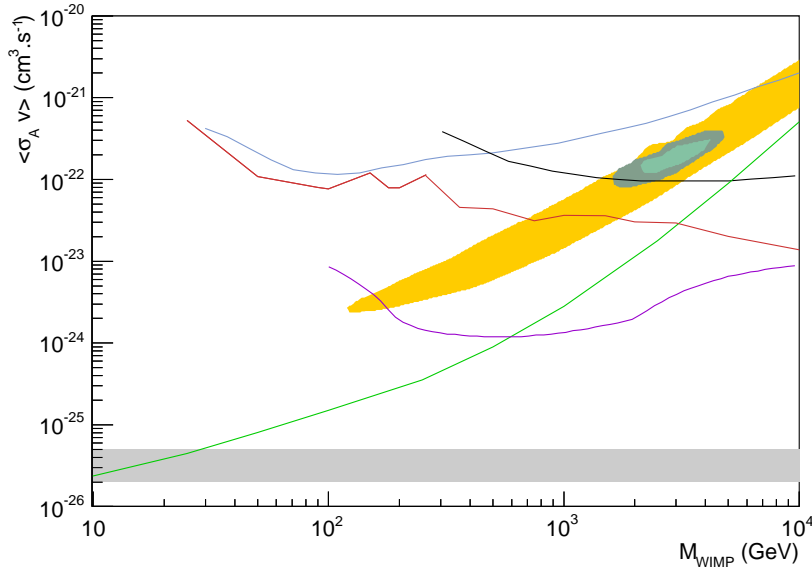


Figure 7: 90% C.L. upper limit set by ANTARES on $\langle \sigma_A \cdot v \rangle$ obtained for the reference $\tau^+\tau^-$ channel (red line). The following limits are also shown: IceCube–DeepCore 79 (2010-2011) for the Galactic Centre (blue line), IceCube–59 (2009-2010) for the Virgo cluster (black line), Fermi-LAT (2008-2010) for the analysis of 10 satellite galaxies (green line) and MAGIC (2011-2013) for Segue 1 (purple line). The regions favored by PAMELA (orange area) and by PAMELA, Fermi-LAT and H.E.S.S. (green ellipses) interpreted as dark matter self-annihilations are also shown. The gray band indicates the natural scale for which all the dark matter is considered to be composed of WIMPs only. See text for references.

6. Summary

The ANTARES neutrino telescope started to take data in 2007. The search for a neutrino diffuse flux has not yielded a neutrino signal and an upper limit on such a flux has been set. Let us note that the sensitivity of ANTARES for

neutrino diffuse fluxes is not very far from the signal observed by IceCube, although still insufficient to confirm it. ANTARES is the most sensitive neutrino telescope for point sources in the southern sky, especially for energies lower than 100 TeV, where most of the neutrino events from a Galactic source are expected to lie. ANTARES can exclude a point source as the origin of the cluster of events observed by IceCube not far from the Galactic Centre. Even a 0.5° extended source is excluded for most of the declinations near the Galactic Centre. Concerning the indirect search for dark matter using neutrinos, ANTARES has been able to set very competitive limits on the flux of neutrinos coming from WIMP self-annihilation in the Sun and the Galactic Centre.

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